ISSN 1047-3289 *J. Air & Waste Manage. Assoc.* **53**:1204–1217

Development of a Microscale Emission Factor Model for Particulate Matter for Predicting Real-Time Motor Vehicle Emissions

Rakesh B. Singh

National Research Council Research Associate, National Exposure Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. Present affiliation: Independent contractor, Kitchener, Ontario, Canada

Alan H. Huber

Atmospheric Sciences Modeling Division, Air Resources Laboratory, National Oceanic and Atmospheric Administration, Research Triangle Park, North Carolina. On assignment to the National Exposure Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina

James N. Braddock

National Exposure Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina

ABSTRACT

The U.S. Environmental Protection Agency's National Exposure Research Laboratory is pursuing a project to improve the methodology for modeling human exposure to motor vehicle emissions. The overall project goal is to develop improved methods for modeling the source through the air pathway to human exposure in significant exposure microenvironments. Current particulate matter (PM) emission models, particle emission factor model (used in the United States, except California) and motor vehicle emission factor model (used in California only), are suitable only for county-scale modeling and emission inventories. There is a need to develop a site-specific real-time emission factor model for PM emissions to support human exposure studies near roadways.

A microscale emission factor model for predicting site-specific real-time motor vehicle PM (MicroFacPM) emissions for total suspended PM, PM less than 10 μm aerodynamic diameter, and PM less than 2.5 μm aerodynamic diameter has been developed. The algorithm used to calculate emission factors in MicroFacPM is disaggregated, and emission factors are calculated from a real-time fleet, rather than from a fleet-wide average estimated by a vehicle-miles-traveled weighting of the emission factors for different vehicle classes. MicroFacPM requires input information necessary to characterize the site-specific real-time fleet being modeled. Other variables required include average vehicle speed, time and day of the year, ambient temperature, and relative humidity.

IMPLICATIONS

Current motor vehicle particulate emission models are designed to estimate county-level emission factors and associated emission inventories. These models are not reliable for real-time emission estimates needed to support human exposure studies. MicroFacPM is designed to estimate emission factors for the U.S. motor vehicle fleet and is suitable for estimating real-time emission factors in microenvironments of human exposure near roadways. This approach is a useful tool to modeling human exposure microenvironments in vehicles and near roadways, and for understanding complex relationships between roadway fixed-site ambient monitoring data and actual human exposure.

INTRODUCTION

Air pollution concentrations vary greatly from place to place at any one time and with time of day and from year to year. The rapid growth in motor vehicle emissions in urban areas of the United States led to significant changes in the automobile provisions of the Clean Air Act Amendments of 1990. The National Research Council (NRC) committee recently identified outdoor measures versus actual human exposure, characterization of emission sources, air-quality-model development, and testing as among the top 10 research areas of highest priority.[1] Another NRC recommendation stated that program plans should include modeling needs relevant to the control of ozone (O_3), hazardous air pollutants, and particulate matter (PM); modeling techniques that might be applicable to future versions of MOBILE[2] and other mobile source emissions models; and strategies and methods to improve the linkages among transportation, mobile source emissions, air quality, and exposure models.[3]

The MOBILE emissions models, including the particulate emission factor model PART (developed by the U.S. Environmental Protection Agency [EPA], used in all states except California) and the EMFAC emissions model (developed by the California Air Resources Board, used in California only) calculate the composite emission factors for each vehicle class by weighting the emission factors calculated for each model year by the travel fraction for that model year and then summing the various weighted factors.[2,4] This method is suitable for larger regional (county)-scale emission estimates and for emission inventories, but it is unsuitable for emission factor estimates in microenvironments critical to human exposure studies. Therefore, an emission factor model for PM within site-specific real-time frameworks needs to be developed to support human exposure studies.

EPA's National Exposure Research Laboratory (NERL) has an ongoing project to improve the methodology for modeling human exposures to motor vehicle emissions. The overall project goal is to develop improved methods for modeling from the source through the air pathway to human exposure, within significant microenvironments of exposure. Roadway dispersion models use the emission factor of particles or gases in terms of concentration per unit distance (e.g., mg/mi) as an input to predict particle or gas concentrations in space or time. Detailed and correct knowledge of emission characteristics is, therefore, an essential prerequisite to developing a reliable human exposure model. The toxicological response of inhaled particles also depends on the particle properties, such as size, number, active surface area, concentration, and physical and chemical characteristics, split into solid and liquid phase; very limited information is available on particulate emission rates except mass-based emission factors. Therefore, emission rates will be discussed in mass per unit distance.

In view of this need, a microscale emission factor model for predicting real-world real-time motor vehicle PM (MicroFacPM) emissions for TSP (total suspended PM), PM_{10} (PM less than 10 μm aerodynamic diameter), and $PM_{2.5}$ (PM less than 2.5 μm aerodynamic diameter) has been developed. The MicroFacPM model uses modeling concepts and structure similar to that used in the development of MicroFacCO.[5,6] The model uses available information concerning the vehicle fleet composition. The algorithm used to calculate emission factors in MicroFacPM is disaggregated, based on the observed site-specific vehicle fleet. The emission factors are calculated from a real-time fleet, rather than from a fleet-wide average estimated by a vehicle-miles-traveled (VMT) weighting of the emission factors for different vehicle classes. MicroFacPM requires input variables that are necessary to characterize the on-road real-time fleet being modeled. Other variables required include average vehicle speed, time and day of the year, ambient temperature, and relative humidity.

This paper discusses the methodology for the development of MicroFacPM. The model is written in FORTRAN 90 for calculating emission factors from vehicular traffic in the United States. It can be run in both batch and interactive modes. Real-time emission rates can be calculated for dates between January 1, 1990, and December 31, 2010, from available vehicle fleet data on an unlimited number of roads and for a maximum of eight lanes of traffic. If more than eight lanes are required, parallel road networks can be modeled. The emission rates for future fleets are estimated with the assumption that there is no change in pollution control and fuel technology and that changes are caused by the replacement of older vehicle fleets with newer ones. A diagram of the MicroFacPM general model structure is shown in Figure 1.

VEHICLE CLASSIFICATION

The motor vehicle fleet is divided into two main categories: light-duty and heavy-duty vehicles. The light-duty vehicles are defined as vehicles with gross vehicle weight (GVW) ratings less than 8500 lb, and heavy-duty vehicles as vehicles with GVW ratings more than 8500 lb. MicroFacPM uses the same extended EPA vehicle classification used in MicroFacCO and MOBILE6.[7,8] The vehicle fleet

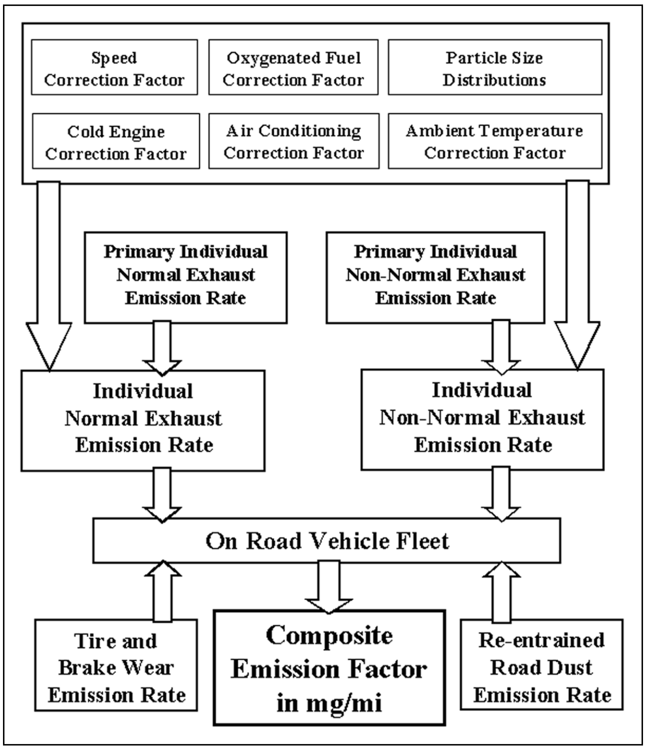

Figure 1. The MicroFacPM general model structure.

classifications, together with their symbols (abbreviations), are presented in Table 1.

INPUT VARIABLES AND OUTPUT OPTIONS

MicroFacPM can be run either in a batch or in an interactive mode. The input parameters required for each specific time interval are job title, number of roads, date, time, smoking vehicle percentage, ambient temperature, relative humidity, vehicle fleet type, output option, roadway type, number of lanes, and average vehicle speed. The model output can be obtained in three categories (options 1, 2, and 3). Option 3 outputs lane-by-lane composite emission rates for the fleet. Option 2 outputs the proportions of PM per vehicle type, model year, and source. Option 1 outputs detailed information on the correction factors applied for each vehicle type and model year.

Table 1. Vehicle classification used in MicroFacPM (extended EPA vehicle classification used in MOBILE6).

Description	GVW (lb)	Symbol
Light-duty gasoline vehicles (cars)	0–6000	LDGV
Light-duty gasoline trucks 1	0–3750	LDGT1
Light-duty gasoline trucks 2	3750–6000	LDGT2
Light-duty gasoline trucks 3	6001–7250	LDGT3
Light-duty gasoline trucks 4	7250–8500	LDGT4
Motorcycles	All	MC
Light-duty diesel vehicles (cars)	0–6000	LDDV
Light-duty diesel trucks 1	0–3750	LDDT1
Light-duty diesel trucks 2	3750–6000	LDDT2
Light-duty diesel trucks 3	6001–7250	LDDT3
Light-duty diesel trucks 4	7250–8500	LDDT4
Heavy-duty gasoline vehicles class 2B	8501–10,000	HDGV2B
Heavy-duty gasoline vehicles class 3	10,001–14,000	HDGV3
Heavy-duty gasoline vehicles class 4	14,001–16,000	HDGV4
Heavy-duty gasoline vehicles class 5	16,001–19,500	HDGV5
Heavy-duty gasoline vehicles class 6	19,501–26,000	HDGV6
Heavy-duty gasoline vehicles class 7	26,001–33,000	HDGV7
Heavy-duty gasoline vehicles class 8A	33,001–60,000	HDGV8A
Heavy-duty gasoline vehicles class 8B	>60,000	HDGV8B
Heavy-duty gasoline school bus	All	HDGSB
Heavy-duty gasoline transit bus	All	HDGTB
Heavy-duty diesel vehicles class 2B	8501–10,000	HDDV2B
Heavy-duty diesel vehicles class 3	10,001–14,000	HDDV3
Heavy-duty diesel vehicles class 4	14,001–16,000	HDDV4
Heavy-duty diesel vehicles class 5	16,001–19,500	HDDV5
Heavy-duty diesel vehicles class 6	19,501–26,000	HDDV6
Heavy-duty diesel vehicles class 7	26,001–33,000	HDDV7
Heavy-duty diesel vehicles class 8A	33,001–60,000	HDDV8A
Heavy-duty diesel vehicles class 8B	>60,000	HDDV8B
Heavy-duty diesel school bus	All	HDDSB
Heavy-duty diesel transit bus	All	HDDTB

Note: Light heavy-duty = class 2B–5; Medium heavy-duty = class 6 and 7; Heavy heavy-duty = class 8A and 8B

VEHICLE FLEET

MicroFac models are developed to use different forms for characterizing the vehicle fleet depending on the availability of information. Similar to MicroFacCO, MicroFacPM has seven options for inputting the vehicle fleet characterization. The model can accept input based on a detailed observed vehicle fleet (options 1 and 2), past vehicle tunnel data (options 3 and 4), video records (options 5 and 6), or a default vehicle fleet (option 7).

EMISSION RATES

Motor vehicle PM includes not only particles exhausted from the tailpipe, but also fugitive sources whose scale and activity rates are poorly known. Vehicle emission rates vary significantly among the different types of vehicles, which can be distinguished by engine type, type of emission control system, vehicle weight, engine capacity, the emission standard to which the vehicle was originally certified, the vehicle's age (which determines the level of technology to which it was built), and the type of fuel used. Up-to-date information was available from MOBILE6 to support the development of MicroFacCO. Presently, similar up-to-date information on PM emission rates for U.S. motor vehicles is not available to support the development of MicroFacPM. Therefore, it is necessary to develop some size-specific PM emission rates for the U.S. vehicle fleet based on what limited information is available.

Exhaust Emission Rates for Light-Duty Vehicles

Light-duty vehicle (<8500 lb) particulate emission rates are calculated in mg/mi by testing a vehicle over a standardized test cycle (known as the Urban Dynamometer Driving Schedule [UDDS]) on a chassis dynamometer. This driving cycle is part of EPA's Federal Test Procedure (FTP), which is used by all motor vehicle manufacturers to certify that their vehicles meet federal tailpipe emission standards. This cycle represents the typical urban area driving pattern, consisting of a series of speed-time profiles. A complete UDDS is divided into three parts—a cold transient portion (Bag 1) comprises the first 3.59 mi (505 sec), Bag 2 comprises the hot stabilized portion of 3.91 mi (867 sec), which is followed by a 10-min soak with the engine off, and then Bag 3 comprises the hot transient portion of 3.59 mi (505 sec).[9] EPA, after recognizing that the UDDS driving cycle does not sufficiently represent all driving conditions, recently introduced a supplemental FTP cycle (SFTP) to address aggressive high-speed driving. This driving cycle is known as US606 and also incorporates the effect of air-conditioning operation (SC03).[10]

The exhaust particulate emission rates used in PART5 are based primarily on tests carried out for an older (pre-1990s) vehicle fleet.[11] Measurements performed on current-technology vehicles, using a variety of fuels, show that emission rates for newer vehicles may be very different from those reported in PART5.[12–24] Therefore, emission studies from several sources were reviewed to calculate more up-to-date emission rates. Starting an engine from cold, or using it under transient driving conditions, has a significant effect on vehicle emissions. Although engines that have not reached proper operating temperature occur in all driving conditions, most are likely during urban driving when short trips occur. Therefore, for microscale modeling, it is necessary to account for both cold- and hot-start running emissions. MicroFac models use UDDS phase 1 (Bag 1) for the cold running emission rate, and phase 2 (Bag 2) and phase 3 (Bag 3) for hot running emission rates (hot running emission rate = $0.521 \times$ phase 2 emission rate + $0.479 \times$ phase 3 emission rate).

In determining the priorities for developing vehicle emission rates, it is necessary to know the on-road vehicle fleet composition. The average vehicle fleet composition in the United States as of July 1996 showed that light-duty vehicles (those with GVWs of 8500 lb or less) comprise 93.68% of the entire vehicle fleet.[25] Within the light-duty class, more than 99% of the vehicles are gasoline-powered (68% cars and 32% trucks). A recent (1999) field study[12] carried out at 61 sites throughout the South Coast Air Basin in California showed that 1.11–1.75% of the vehicles in the light-duty fleet emitted visible smoke. This fleet was comprised mainly of older vehicles, 8–18 yr of age. The contribution of smoking vehicles was estimated to be 24–35% of the total particulate emissions inventory for light-duty vehicles. While the fleet in this study may not be representative of the nationwide fleet, it does demonstrate the importance of fleet composition in identifying the proportions of normal emitters versus high-emitting (non-normal or smoking) gasoline vehicles.

Gasoline. Testing performed on older unleaded gasoline (catalyst and noncatalyst) normal emitters reported higher PM emission rates compared with newer normal emitting vehicles, whose emission rates varied from 0.1 to 10 mg/mi.[13–22,26–29] The exhaust PM emissions were significantly reduced (by factors of 0.58, 0.63, 0.70, and 0.68 for Tier 0 LDGV, Tier 0 LDGT, Tier 1 LDGV, and Tier 1 LDGT vehicles, respectively) with the use of oxygenated fuel during the cold start on the UDDS cycle.[30,31] PM emissions were dependent on driving cycle, vehicle type, driving behavior, vehicle condition, vehicle weight, fuel control system, and emission control system. The studies discussed previously have divided normal and high-emitting vehicles-based on their gaseous emission profiles. Our definition of normal and non-normal vehicles is not based on their gaseous emissions. We define normal-emitting vehicles as those vehicles that have no visible smoke, while non-normal emitting vehicles are defined as those vehicles that have visible smoke emitted from the tailpipe. Because of the limited amount of data in three UDDS operating phases, no attempt was made to separate non-normal emitter vehicle emission rates into cold- and hot-operating modes. Non-normal total-derived PM emission rates were found to be between 19 and 1341 mg/mi.[18,32,33]

Diesel. The U.S. light-duty diesel fleet vehicle composition is less than 1% of the gasoline light-duty fleet. The average PM emission rates from diesel light-duty vehicles are ~1–2 orders of magnitude higher than their gasoline counterparts.[19] PART5 lists the emission rates from light-duty diesel vehicles and trucks per their age varying from 100 to 309 mg/mi for vehicles from 1981 and up, and from 700 mg/mi for pre-1981 vehicles.[11] Studies on older diesel engines have reported even higher values[18,34,35] compared with new diesel engines that now use low-sulfur fuel.[18,36] The aim is to determine the emission rates from the present on-road vehicle fleet; therefore, our analysis to calculate the emission rates for normal and non-normal categories is from the work carried out by Norbeck et al.[18] The ratio between cold and hot emissions in this case is approximately the same as that found in European studies.[36] The calculated running hot (from phase 2 and 3 of UDDS cycle) and cold (from phase 1 of UDDS cycle) mass-based PM emission rates (TSP in mg/mi) from a literature survey for the light-duty vehicle fleet together with sample size and range observed are shown in Table 2. It is assumed that the average values in Table 2 are most likely to represent the real-world vehicle fleet.

Exhaust Emission Rates for Heavy-Duty Vehicles

The testing of heavy-duty vehicles to determine PM emission rates is performed either on chassis dynamometers or on engine dynamometers. The first approach is similar to those used to test light-duty vehicles. The second method involves removing the engine from a test vehicle's chassis, mounting it on a test stand, and operating the engine on a testing apparatus (i.e., engine dynamometer). In this case, the emission rates are determined in grams per brake-horsepower-hour (g/bhp-hr) by testing the engine over a heavy-duty transient driving cycle.[37] The heavy-duty transient test (HDTT) cycle simulates heavy-duty vehicle operation in urban areas and was developed from instrumented heavy-duty vehicles that operated in New York City, from freeway driving in Los Angeles, and also from nonfreeway driving in Los Angeles.[9] The emission rates in mg/mi are estimated by multiplying the emission rates in mg/bhp-hr by a conversion factor in bhp-hr/mi.

Table 2. Running hot and cold mass-based PM emission rates (TSP in mg/mi) for light-duty vehicles.[17,18,22,31–33]

Vehicle Age	Sample Size	Emission Rates (mg/mi) Average	Median	Range
LDGV normal emitters: hot running emission rates				
Tier 1 (1993+)[18,22,31]	39	0.49	0.43	0.01–1.28
Tier 0 (1981–1993)[17,18,31]	47	4.74	1.8	0.01–42.6
Pre-1981[18,22]	8	27.04	27.22	2.95–63.76
LDGV normal emitters: cold running emission rates				
Tier 1 (1993+)[18,22,31]	39	5.18	1.9	0.43–18.2
Tier 0 (1981–1993)[17,18,31]	47	18.66	6.77	0.6–71.6
Pre-1981[18,22]	8	46.05	49.58	3.66–78.91
LDGT normal emitters: hot running emission rates				
Tier 1 (1993+)[18,31]	17	1.83	1.04	0.43–5.78
Tier 0 (1981–1993)[18,31]	46	7.4	3.6	0.28–53.14
Pre-1981[18]	6	17.79	16.35	5.7–37.54
LDGT normal emitters: cold running emission rates				
Tier 1 (1993+)[18,31]	17	14.33	3.63	1.52–44.67
Tier 0 (1981–1993)[18,31]	46	20.98	10.77	0.53–87.65
Pre-1981[18]	6	104.16	81.82	30.1–200.24
LDGV and LDGT non-normal emitters: running (hot or cold) emission rates				
All[18,32,33]	26	422.1	333.6	19–1341
LDDV and LDDT normal emitters: hot running emission rates				
All[18]	17	375.31	364.5	15.9–794
LDDV and LDDT normal emitters: cold running emission rates				
All[18]	17	804.13	721.1	14.5–2442.5
LDDV and LDDT non-normal emitters: running (hot or cold) emission rates				
All[18]	2	1505.35	1505.35	1402.4–1608.3

Other chassis dynamometer driving cycles, such as the New York City Cycle (NYCC), which is representative of driving in heavily congested inner city areas;[9] the Central Business District (CBD) Cycle, which simulates inner-city driving conditions through repeated accelerations, decelerations, and idle periods;[38] and the West Virginia 5-Peak or Truck (WVT) Cycle also are commonly used.[39]

In July 1996, heavy-duty vehicles (including buses) comprised ~6.32% of the entire vehicle fleet.[25] The breakdown (or percent composition) of heavy-duty vehicles includes class 2B, class 3, class 4, class 5, class 6, class 7, class 8A, class 8B, school buses, and transit buses, and their percent composition is as follows: 50.2, 4.44, 3.29, 2.93, 9.15, 9.65, 4.96, 11.43, 3.48, and 0.47, respectively. Diesel vehicles dominate all heavy-duty fleet categories except for light heavy-duty vehicle class 2B, which has ~80% gasoline-powered vehicles.

Gasoline. Very little information is available for the PM emission rates from heavy-duty gasoline vehicles. As discussed earlier, there are few gasoline vehicles outside of class 2B. Therefore, it is assumed that emission factors from gasoline heavy-duty vehicles for class 2B increase with fuel consumption with reference to the light-duty gasoline truck. The estimated gasoline fuel consumption in 1996 for heavy-duty class 2B gasoline vehicles was 10.1 miles per gallon (mpg). The PM emission rates from light heavy-duty vehicles are estimated to be 1.5 (for class 2B) to 2 times (for class 3 and higher) greater than those of light-duty gasoline trucks, which are assumed to have a fuel economy of 15 mpg.

Diesel. In general, new heavy-duty diesel-powered vehicles emit much less PM compared with older vehicles. Under the EPA certification test procedure, manufacturers are required to submit emissions data on new engines by using engine dynamometer test results. The up-to-date emission rates are based on the assumption that the emission levels produced by the certification test procedures are representative of the average in-use emission levels. These data are available from the MOBILE6 model. Tables 3a and 3b presents the PM emission rates (mg/mi) for heavy-duty diesel-powered vehicles derived from MOBILE6 sources. The emissions from pre-1990 vehicles will increase with age because of more vehicle miles accumulated and because of the deterioration of the vehicles' emission control systems.

Nonexhaust Emission Rates

Additional sources of motor vehicle particulate emissions include tire wear, brake wear, and re-entrained road material. Limited testing has been carried out to estimate the contribution of brake-wear and tire-wear emissions. Brake-wear and tire-wear particles are emitted from different types of vehicles at different rates, but because of a lack of data, the rate for cars is used for all vehicle types. The particulate emission rate for brake wear, measured on braking cycles representative of urban driving, averaged 0.0128 g/mi for cars,[40] and the emission rate for airborne tire-wear particles for cars has been estimated at 0.002 g/mi.[41,42] The PART5 model uses these values. In the absence of any new information, MicroFacPM uses the same values discussed previously and used in PART5. The

Table 3a. Mass-based PM emission rates (TSP) for HDDVs.

	Emission Rates (mg/mi) + Deterioration (mg/10,000 mi)			
	1994+	1991–1993	1990	Pre-1990
HDDV2B	98	252	418	484 + 1.1
HDDV3	128	328	542	627 + 1.4
HDDV4	131	337	561	652 + 1.5
HDDV5	143	371	622	675 + 1.7
HDDV6	155	390	744	864 + 4.4
HDDV7	191	477	905	1046 + 4.4
HDDV8A	224	596	1091	1271 + 2.9
HDDV8B	245	655	1208	1412 + 3.2

brake-wear emission rates are applied only for urban roads. To obtain tire-wear emission rates from the vehicles, the tire emission rate is multiplied by the number of wheels on the vehicle. The number of wheels is the default value per vehicle class in the model.

The empirical emission model for unpaved roads was developed from a broad database[43] and shows good agreement with field results.[44,45] For paved roads, the algorithm was based on the results of a limited number of emission tests and, therefore, may not represent all urban paved road conditions.[46] Zimmer et al.[46] concluded that the paved road equation should not be applied to cases where the range of silt loadings is outside the range used to develop the equation (i.e., urban roads with silt loading ranging from 0.02 to 1 g/m^2) and there is a need for improving the emission factors algorithms. The results show that the empirical equation for paved roads tends to overpredict the emission factors.[44,46–48] Because the methodology for re-entrained road dust needs to be revised, the current version of MicroFacPM does not account for re-entrained road dust (at least until new data become available). However, if needed, the re-entrained road dust emission rates and methodology in MicroFacPM may be used in a similar manner to that in PM-FAC.[49]

COLD-START VERSUS HOT-START EXHAUST EMISSIONS

MicroFacPM fully accounts for the distance traveled by vehicles during a cold-start operating mode in calculating the composite emission rates. The MicroFacPM cold-start function goes to zero effect after a few miles, depending upon ambient temperature. The method is relatively simple and does not assume the cold and hot operating mode proportions arbitrarily. This methodology is similar to that used in MicroFacCO[5] and is summarized later.

Cold mileage percentage for a model year is calculated as follows:

$$CMP_{i,j} = 0.698 - 0.051 \times (ltrip_{i,j} \times 1.6) - (0.01051 - 0.00077 \times ltrip_{i,j} \times 1.6) \times TC \quad (1)$$

where $CMP_{i,j}$ is the cold mileage percentage for vehicle type *i* and model year *j*, *TC* is the ambient air temperature (°C), and $ltrip_{i,j}$ is the length of the trip (mi) for vehicle type *i* and model year *j*.

Length-of-trip data for light-duty gasoline vehicles, trucks class 1 and 2 (<6000 lb), and trucks class 3 and 4 (6001–8500 lb) are calculated based on trips per day and miles per day data.[50] The length of these trips are defined in the model according to the type of vehicle and model year. In MicroFacPM, the effect of cold mileage percentage is considered only for light-duty vehicles with gasoline engines (LDGV and LDGT), because all other vehicles are assumed to be running with hot engines. The model accounts for the cold-engine operating mode based on the vehicle type, model year, and ambient temperature. These estimates can be further refined if the length of trips for different model years and vehicle classes can be assigned for a roadway type. Default values for specific studies can also be input to MicroFacPM.

ROADSIDE SURVEYS

MicroFac models are designed to estimate site-specific on-road emission factors at a microscale level and accepts the user's estimate of high emitters (smoking vehicles) based on local roadside surveys (or other method) as input. An analysis of 59,000 in-use vehicles between 1985 and 1992 observed that some high emitters were found in nearly every model year, but the highest tailpipe emissions came from vehicles ~10 yr old.[51] Pre-1975 vehicles were not included in this study. Another recent field study, carried out at 61 sites throughout the South Coast Air Basin in California, showed that 1.11–1.75% of the vehicles in the light-duty fleet emit visible smoke.[12] Therefore, if estimated values for the fleet categories based on local estimates or measurements are not available, then MicroFacPM uses the default value for smoking (i.e., high-emitting)

Table 3b. Mass-based PM emission rates (TSP) for HDDBs.

	Emission Rates (mg/mi) + Deterioration (mg/10,000 mi)					
	1996+	1994–1995	1993	1991–1992	1990	Pre-1990
HDDSB	118	171	644	1258	1015	1156 + 2.6
HDDTB	186	277	1059	2112	1740	2112 + 4.6

Table 4. Mass-based PM_{10} and $PM_{2.5}$ percentage (in comparison to TSP) for U.S. vehicle-generated PM sources.[18,58,59]

	Sample Size	PM_{10} (%) of TSP			$PM_{2.5}$ (%) of TSP		
		Average	Median	Range	Average	Median	Range
LDGV Tier 1 (1993+): normal emitter	14	83.5	83.1	59.1–100	73.2	74.2	40.9–100
LDGV Tier 0 (1981–1993): normal emitter	26	89.6	90.8	76.9–100	82.4	83.2	71.8–96.7
LDGT Tier 1 (1993+): normal emitter	8	81.6	85.4	32.3–100	74.8	81.1	32.2–97.8
LDGT Tier 0 (1981–1993): normal emitter	35	88.6	92.9	51.5–100	81.5	88.7	45.5–100
LDGV& LDGT (Pre-1981): normal emitter	12	96.1	96.6	89.7–99.4	91.7	94.5	77.6–98
LDDV& LDDT (All): normal emitter	17	99.4	99.8	96.8–100	95.4	96	89.3–99.8
LDGV& LDGT (All): non-normal emitter	3	99.8	99.8	99.5–100	99.3	99.4	98.8–99.8
LDDV& LDDT (All): non-normal emitter	2	99	99	98.7–99.3	92.3	92.3	87.8–96.8
Heavy-duty diesel vehicles	15	98.7	99.5	95.4–100	96.9	97.8	92–100

vehicles depending on the average age of the fleet (e.g., for 10-yr-old fleet as 1% and for 15-yr-old fleet as 1.5%).

SPEED CORRECTION FACTORS

The UDDS driving cycle measures emission rates at an average speed of 19.6 mi/hr; therefore, emission rates have to be corrected for on-road average speeds. There is little information available for the change in emission levels associated with speeds for U.S. motor vehicles. Therefore, MicroFacPM speed correction factors were derived from similar European studies.[36,49,52–54] The following speed correction factors are used in the model for heavy-duty diesel vehicles:

For light heavy-duty diesel vehicles

$$\begin{aligned} &= 1.0(V \leq 12.5 \text{ mi/hr}) \\ &-0.0321\text{V} + 1.4013(V = 12.5 \text{ to } 25.0 \text{ mi/hr}) \\ &-0.0053V + 0.7303(V > 25.0 \text{ to } 50.0 \text{ mi/hr}) \\ &0.47(V > 50.0 \text{ mi/hr}) \end{aligned} \tag{2}$$

For medium heavy-duty diesel vehicles

$$\begin{aligned} &= 1.0(V \leq 11.9 \text{ mi/hr}) \\ &-0.0243V + 1.2881(V = 11.9 \text{ to } 27.5 \text{ mi/hr}) \\ &-0.0035V + 0.7168(V > 27.5 \text{ to } 50.0 \text{ mi/hr}) \\ &0.54(V > 50.0 \text{ mi/hr}) \end{aligned} \tag{3}$$

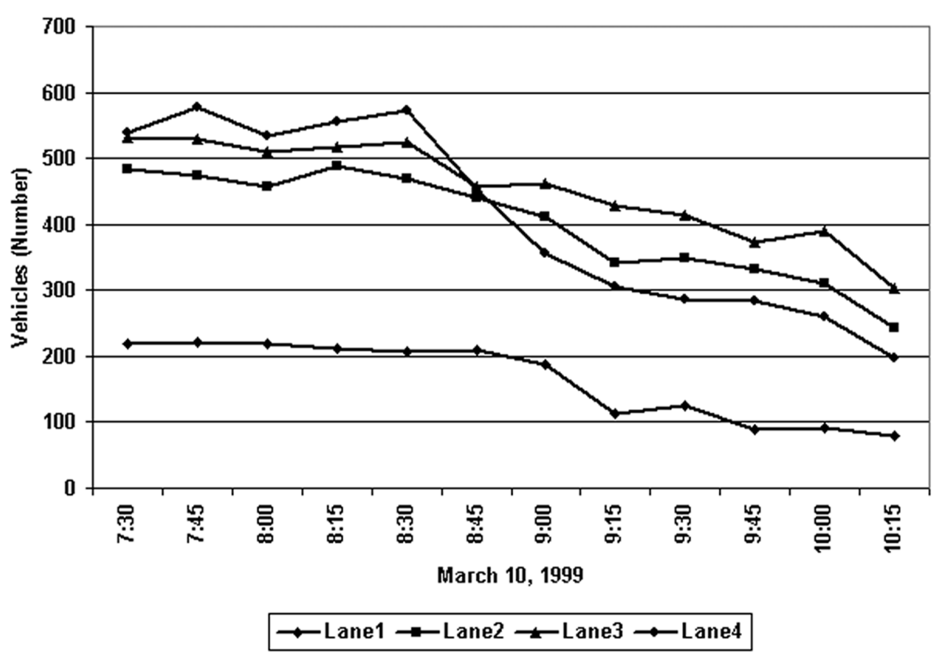

Figure 2. Vehicle fleet separated at 15-min time intervals on March 10, 1999, at I-40 between 7:30 and 10:15 a.m.

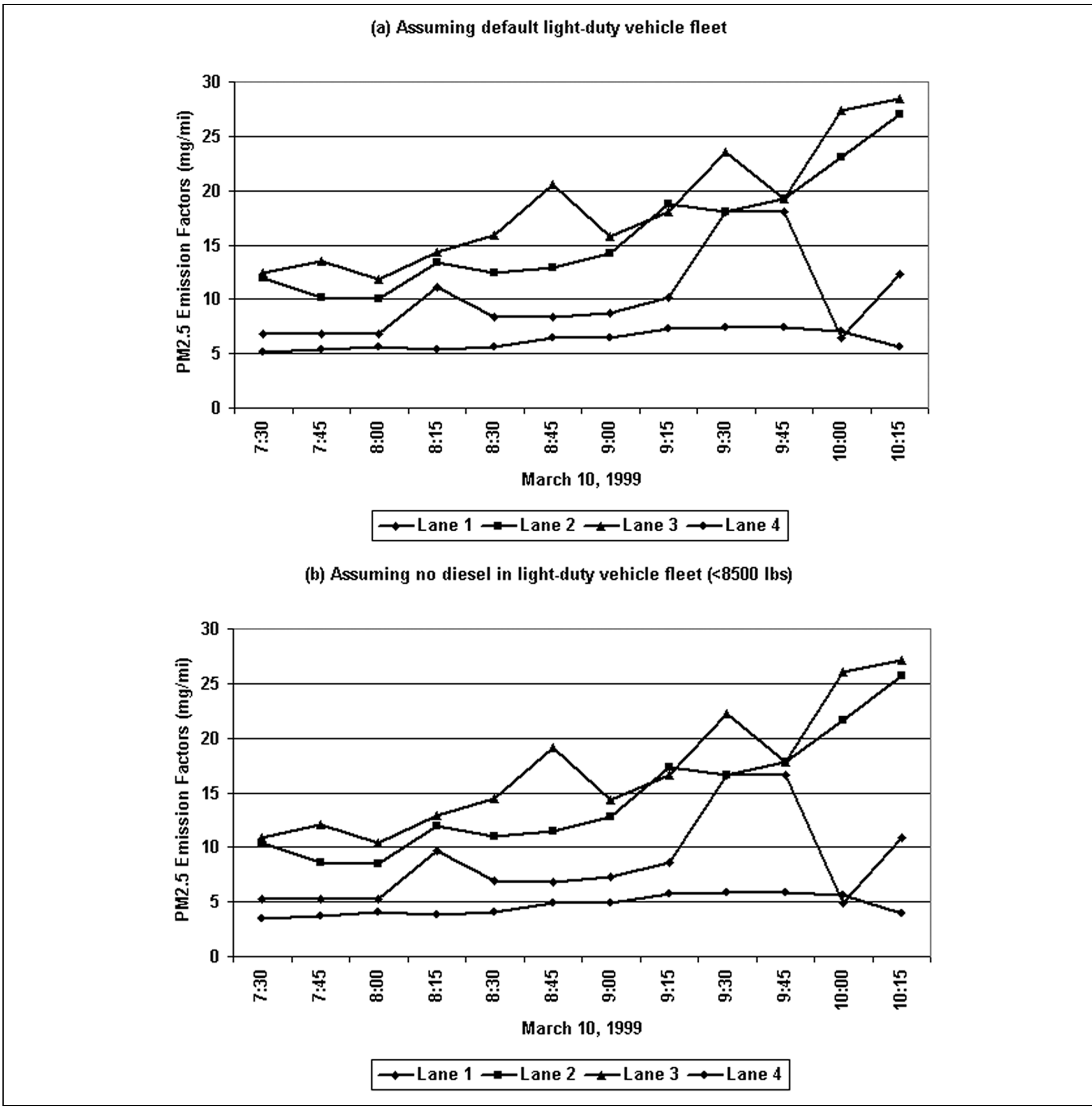

Figure 3. Real-time $PM_{2.5}$ exhaust emission factors on March 10, 1999, at I-40 between 7:30 and 10:15 a.m.

$$\begin{aligned}
&\text{For heavy heavy-duty} \\
&\text{diesel vehicles (including buses)} \\
&= 1.0(V \leq 12.5 \text{ mi/hr}) \\
&-0.0228V + 1.2846(V = 12.5 \text{ to } 29.4 \text{ mi/hr}) \\
&-0.0023V + 0.6833(V > 29.4 \text{ to } 50.0 \text{ mi/hr}) \\
&0.57(V > 50.0 \text{ mi/hr})
\end{aligned} \tag{4}$$

where V is speed in mi/hr. Because of the limited amount of data, no attempt was made to apply speed correction factors for light-duty and heavy-duty gasoline-fueled vehicles. The equations show that emission rates dropped to approximately half with an increase of speed from 12 to 50 mi/hr. Most of the emission reduction took place (by a factor of 0.6) with an increase of speed from ~12 to 27 mi/hr.

AIR CONDITIONING CORRECTION FACTOR

MicroFacPM accounts for the exhaust emissions correction factors resulting from air-conditioning operations based on their fuel consumption for light-duty gasoline vehicles and trucks. The methodology has been adopted from the recommendations made in the MOBILE6 model.[55–57]

PARTICLE SIZE DISTRIBUTIONS

Particle size distributions are different for both gasoline-powered and diesel-powered vehicles. They also vary depending upon the various driving cycles, speed, and loads.[11,49] Current engine technology and fuel(s) are different from those vehicles that were used to derive particle size distribution in PART5. In addition, PART5 size distribution does not account for the age of the vehicles. Therefore, MicroFacPM size distribution is based upon recent literature reviews.[18,58,59] The PM emission rates previously discussed represent TSP emissions only. The emission rates discussed in this paper are mass-based; therefore, particle size distribution is mass-based. The mass-based particle size values for PM_{10} and $PM_{2.5}$ are shown in Table 4; percentage values shown are the percentage of mass in comparison with TSP. The particle size distribution for tire wear and brake wear is the same as that used in PART5. These particle size distributions will be updated as more information becomes available.

COMPOSITE EMISSION RATES

The MicroFacPM composite emission rate for the vehicle fleet is calculated by incorporating all the various parameters discussed previously. The model first calculates the emission rates and fraction of vehicles in each category over a 25-yr age distribution for both normal and non-normal emitting categories. Then vehicle miles accumulated for heavy-duty vehicles are calculated as a function of date, to account for deterioration rates. This approach helps in calculating average vehicle miles accumulated any time in a year. October is the reference month because sales for the new model year start from October. The first "year" is calculated as

$$\text{Year} = (\text{Month} + 2 + (\text{Day}/30))/(2 \times 12) \tag{5}$$

For example, mileage for April 15, 1998, is calculated as [4 + 2 + (15/30)]/(2 × 12).

Then the model calculates speed correction factors and corrects the normal and non-normal emission rates for speed. Finally, cold start percentage and air-conditioning correction factors in accordance to vehicle type and model year are incorporated, and composite emission rates for individual vehicles are calculated as follows:

$$\begin{aligned} ER_{i,j} = [\{(NER_{i,j} * V_i + ColdT_{i,j}) * CMP_{i,j} + NER_{i,j} * V_i \\ * (1 - CMP_{i,j})\} * (1 - fail) * (1 + AC_i * ACV_{i,j} - ACV_{i,j}) \\ + \{(BER_{i,j} * V_i + ColdT_{i,j}) * CMP_{i,j} + BER_{i,j} * V_i \\ * (1 - CMP_{i,j})\} * fail * (1 + AC_i * ACV_{i,j} - ACV_{i,j})] \end{aligned} \tag{6}$$

where $ER_{i,j}$ is the composite emission rate for vehicle type *i* and model year *j*, $NER_{i,j}$ is the normal emission rate for vehicle type *i* and model year *j*, $BER_{i,j}$ is the non-normal emission rate for vehicle type *i* and model year *j*, $ColdT_{i,j}$ is the temperature correction factor for the cold operating mode (multiplicative for model year pre-1980) for vehicle

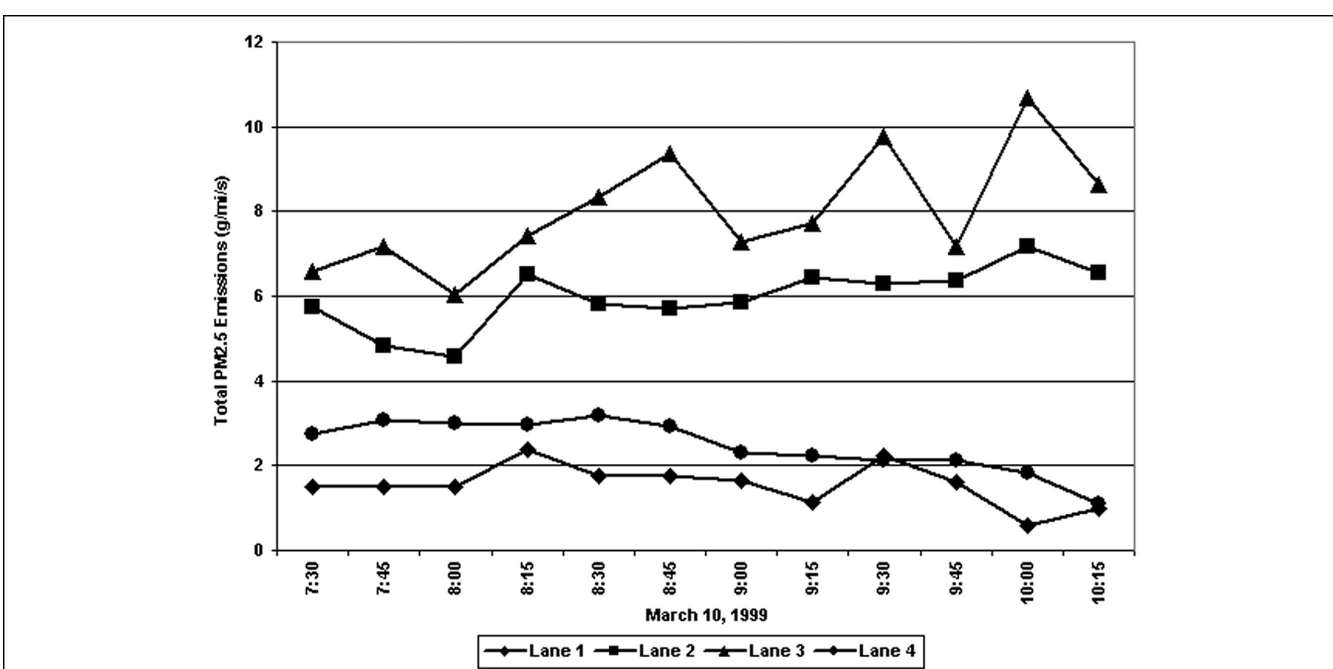

Figure 4. Real-time $PM_{2.5}$ exhaust emission factors on March 10, 1999, at I-40 between 7:30 and 10:15 a.m.

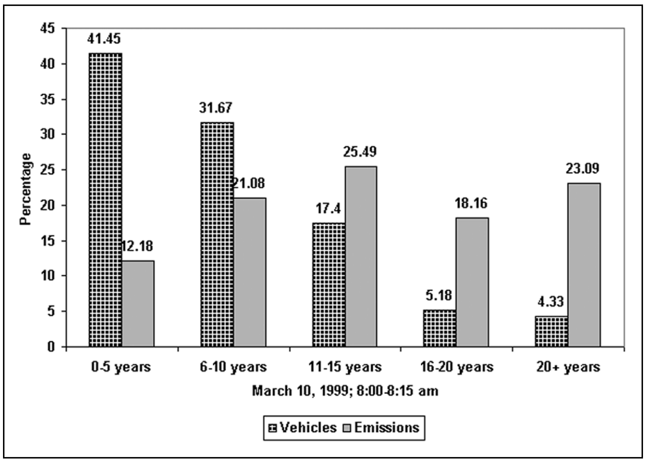

Figure 5. Contribution of $PM_{2.5}$ exhaust emission per vehicle on March 10, 1999, at I-40 on Lane 2 between 8:00 and 8:15 a.m.

type *i* and model year *j*, $CMP_{i,j}$ is the cold mileage percentage for vehicle type *i* and model year *j*, *Fail* is the percentage of smoking (non-normal emitting) vehicles, AC_i is the air conditioning correction factor for vehicle type *i*, $ACV_{i,j}$ is the fraction of vehicles with air conditioning for vehicle type *i* and model year *j*, and V_i is the speed correction factor for vehicle type *i*.

These emission rates (mg/mi) are then multiplied by the fraction of vehicles of each model year and vehicle class. Proportions of emissions (mg/mi) are calculated for each model year and vehicle class.

$$CEF_{i,j} = ER_{i,j} \times VEH_{i,j} \tag{7}$$

where $CEF_{i,j}$ is the proportion of composite emission factor for vehicle type *i* and model year *j*, and $VEH_{i,j}$ is the fraction of vehicles for vehicle type *i* and model year *j*.

Finally, these proportions are summed to obtain the composite emission factor for the entire fleet.

$$CEF = \sum_{i,j} CEF_{i,j} \tag{8}$$

APPLICATION

An application of MicroFacPM calculation of real-time $PM_{2.5}$ emission factors for March 10, 1999, at a location along Interstate Highway 40 in the Research Triangle Park area of North Carolina is presented here. Interstate 40 (East) is a main route for traffic commuting between Raleigh and Research Triangle Park. The traffic fleet was recorded in the morning hours on videotape between 7:15 and 10:15 a.m. and then analyzed manually (watching the video tape in slow motion) for the vehicle type (light-duty vehicles <6000 lb, light-duty trucks <8500 lb, and heavy-duty vehicles >8500 lbs), lane-by-lane, and separated into 15-min time intervals (Figure 2). The number of vehicles recorded in lane 1 (which is both the slowest and the exit lane) was very low compared with the other three lanes. Lane 4 had the fastest traffic, and very few heavy-duty vehicles were recorded in this lane. The average heavy-duty vehicle percentage was ~3, 7, 9, and 1% in lanes 1, 2, 3, and 4, respectively. In general, the number of heavy-duty vehicles increased with time. The total traffic was quite consistent between 7:15 and 8:30

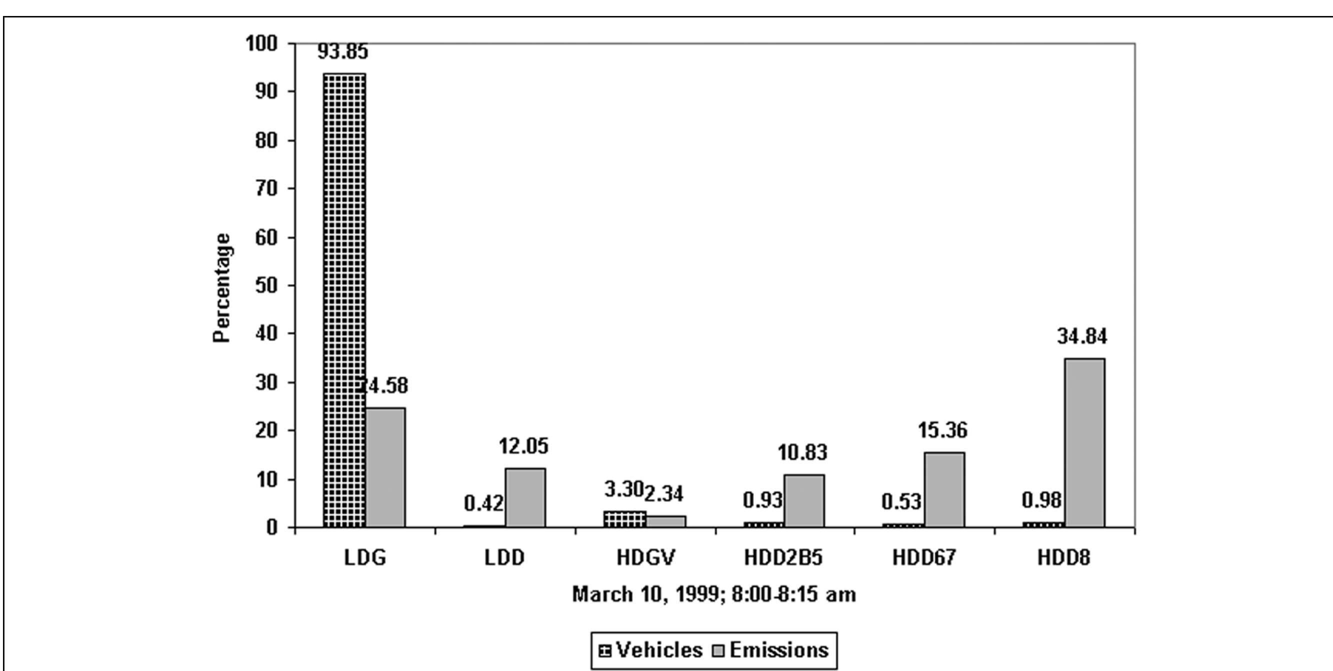

Figure 6. Contribution of $PM_{2.5}$ exhaust emission factors per vehicle class on March 10, 1999, at I-40 on Lane 2 between 8:00 and 8:15 a.m.

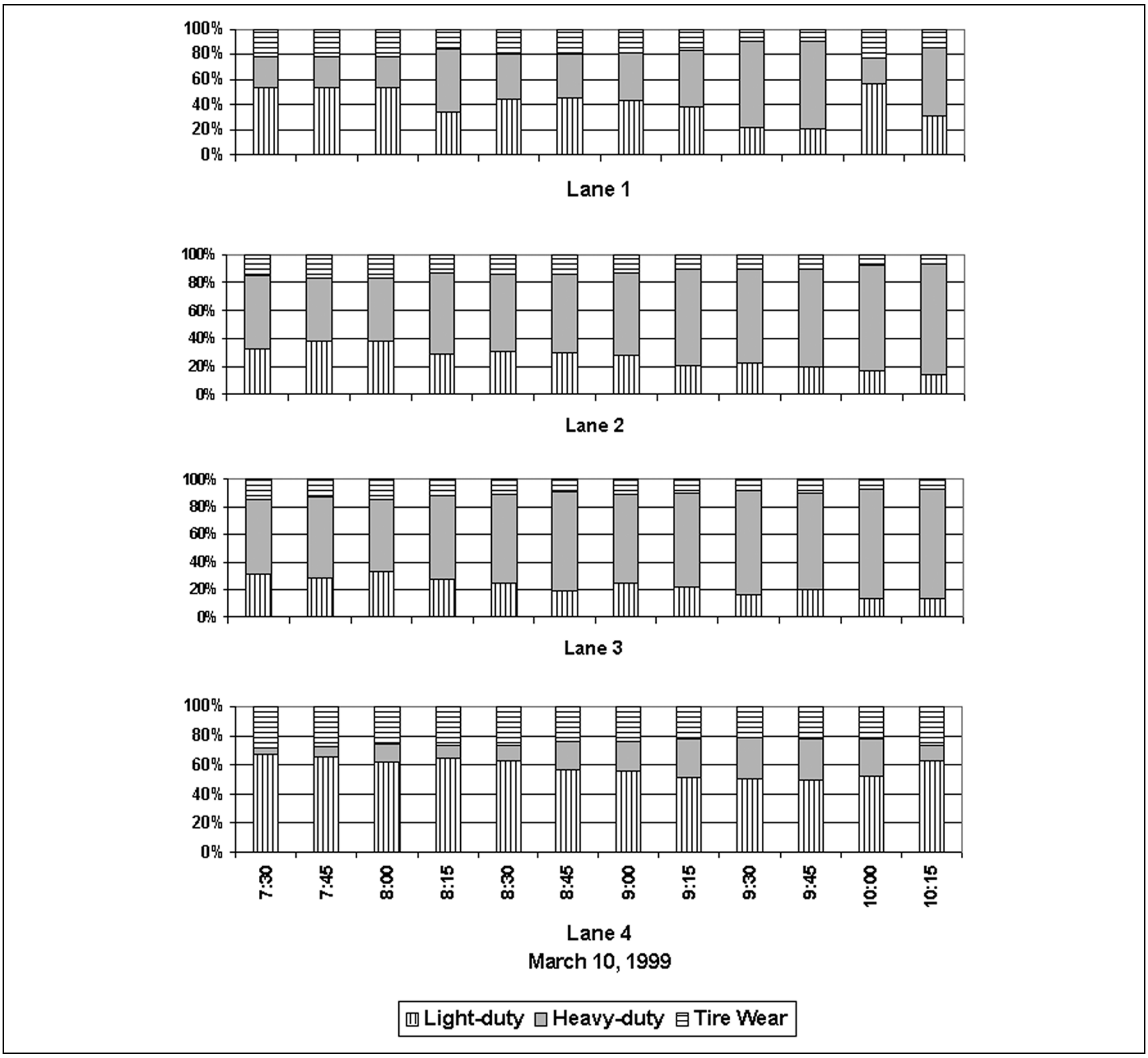

Figure 7. Contribution of light-duty exhaust, heavy-duty exhaust, and tire-wear $PM_{2.5}$ emission factors on March 10, 1999, at I-40 between 7:30 and 10:15 a.m.

a.m., but dropped significantly after 8:30 a.m., especially between the 10:00 a.m. and 10:15 a.m. time periods. Therefore, the percentage of heavy-duty vehicles is significantly higher late in the morning.

The calculated real-time exhaust $PM_{2.5}$ emission factors at 15-min intervals are shown in Figure 3. In these calculations, the on-road age-wise distributions for light-duty vehicles (LDGV, LDDV, LDGT12, LDDT12, LDGT34, and LDD34) were assumed from the registrations of Wake and Durham County areas. The percentage of diesel vehicles in the light-duty vehicles fleet (<8500 lb) is ~0.54% only. For heavy-duty vehicles, the composition and age-wise distribution was assumed to be the average U.S. vehicle fleet makeup for 1996.[61,62] The model was run assuming nonoxygenated fuel, hot-stabilized vehicles, no smoking vehicles in the fleet, and average speeds greater than 50 mi/hr for all runs. The emission factors vary from 6.38 to 18.08 mg/mi in lane 1, 10.03 to 27.03 mg/mi in lane 2, 11.84 to 28.39 mg/mi in lane 3, and 5.08 to 7.43 mg/mi in lane 4 (see Figure 3a). Although the percentage of the light-duty diesel fleet is very small (~0.54%), this does have an effect of composite exhaust $PM_{2.5}$ emission factors. Assuming no diesel vehicles in the light-duty fleet, the resulting exhaust $PM_{2.5}$ emission factors are shown in Figure 3b. If the fleet is dominated mainly by light-duty vehicles (lane 4), then emission factors dropped significantly, varying from 3.52 to 5.89 mg/mi. Figure 4 shows the overall exhaust $PM_{2.5}$ emissions in g/mi/sec (by incorporating the number of vehicles lane-by-lane) needed for the exposure assessment. The emissions vary from 0.4 to 2 g/mi/sec for lane 1, 3.9 to 6.7 for lane 2, 5.3 to 10.2 for lane 3, and 0.8 to 2.3 for lane 4; minimum and maximum emissions calculated were between 9:45 and 10:00 a.m. for lane 1 (0.4 g/mi/sec) and lane 3 (10.2 g/mi/sec), respectively.

Figures 5 and 6 show the contribution of exhaust $PM_{2.5}$ emissions from vehicles of different ages and types for the time interval between 8:00 and 8:15 a.m. on lane 2. Although the percentage of vehicles in the 0–5 yr age group is the largest (41%), their contribution to $PM_{2.5}$ is relatively small (12%) (see Figure 5). Similarly, the very small percentage (less than 2%) of diesel vehicles contributes the most significant percentage (62%) of all $PM_{2.5}$ emissions (see Figure 6). Figure 7 groups the emissions into light-duty exhaust, heavy-duty exhaust, and tire-wear $PM_{2.5}$ emissions lane-by-lane. If we compare the emissions at different temporal distributions, then variation is evident, which shows the importance of the disaggregated model. For example, in lane 1, the contribution from heavy-duty vehicles is very large for the 15-min time periods ending at 9:45 a.m. and 10:15 a.m., as compared with the 10:00 a.m. time period. In general, contributions from heavy-duty exhaust emissions are maximized in lane 3 and minimized in lane 4. The traffic is free flowing; therefore, the brake-wear emission factor is assumed to be zero. These examples demonstrate four ways that MicroFacPM may be applied to provide site-specific emission information, which is critical to providing local emission estimates. More examples and sensitivity studies are presented in a companion paper entitled "Sensitivity Analysis and Evaluation of MicroFacPM: A Microscale Motor Vehicle Emission Factor Model for PM Emissions."[60]

The complete modeling framework from source to exposure was discussed by the authors in a paper "Modeling and Measurement of Real-Time CO Concentrations in Roadway Microenvironments," which demonstrated the use of the emission model in modeling roadway air concentrations through an example, and discussed the issues and research needs for improving the methodology of modeling human exposures to mobile source emissions.[63] Figure 8 shows that the emissions model feeds a dispersion model to support microenvironmental modeling. The roadway dispersion model will provide ambient air concentrations resulting from transport and dispersion of the roadway emissions. The microenvironmental model considers factors in a more refined manner than do the air dispersion models, which are specific to the particular exposure microenvironment (e.g., standing by the roadside or actually inside the vehicle, inside the moving vehicle). Estimates of how emissions inside the vehicle would contribute directly to the in-vehicle microenvironment can be made without the need for an air dispersion model. The roadside microenvironmental air pollutant concentrations are impacted both by a general contribution from emissions upwind along the roadway, which may be modeled by an air dispersion model, and by a localized specific complex flow generated by the local terrain and vehicles. The local model may need to be more refined than can be specified by a general dispersion model. Refined modeling using Computational Fluid Dynamics (CFD) models will be used to develop refined dispersion models and a microenvironmental model. Measurement databases from past research and special new studies as part of this project will be used to both support and evaluate the emission, dispersion, and microenvironmental models. The goal is to have a modeling system that can be used to simulate potential exposure factors to mobile source emissions within mobile source microenvironments. These generalized factors would be appropriately incorporated into population-based human exposure models.

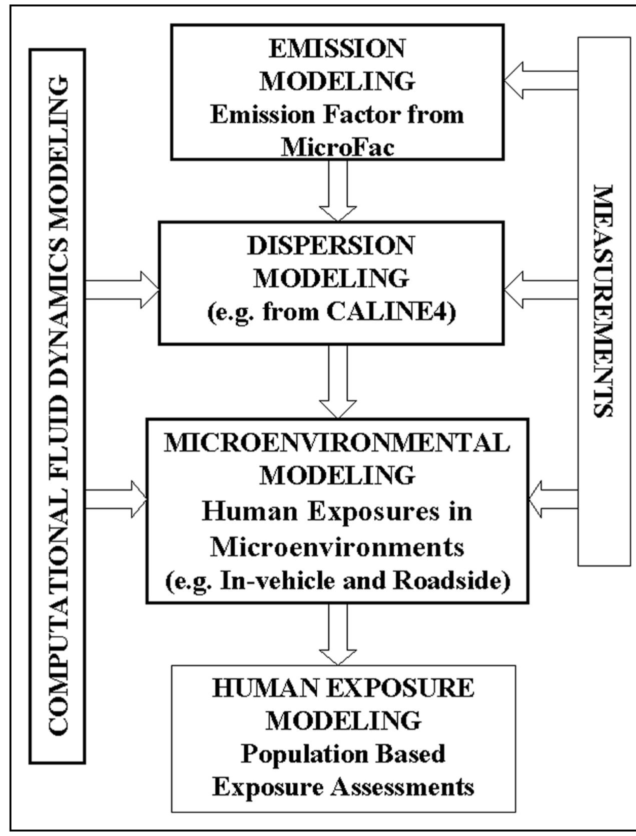

Figure 8. Modeling the source through the air pathway to human exposure.

SUMMARY

The methodology for the development of a microscale emission factor model, MicroFacPM, for predicting real-time motor vehicle PM emissions is presented. This model captures virtually all the real-world information for the U.S. motor vehicle fleet. The methodology for MicroFacPM uses existing databases. No new emission measurement databases are developed in this study. The algorithm used to calculate emission factors in MicroFacPM is disaggregated. MicroFacPM calculates emission factors in real-time from an on-road vehicle fleet, not for an aggregated fleet-wide average estimated by VMT as in the methodology for the PART model. MicroFacPM has been designed to estimate emission factors from on-road traffic and can be used directly to support reliable modeling of human exposures near roadways and inside vehicles traveling along the roadways. MicroFacPM should be applied where local site-specific information is available or good estimates can be assumed to support the model application. The sensitivity analysis and evaluation of MicroFacPM is discussed separately in the companion paper entitled "Sensitivity Analysis and Evaluation of MicroFacPM: A Microscale Motor Vehicle Emission Factor Model for PM Emissions."[60]

DISCLAIMER

EPA, through its Office of Research and Development, funded the research described here. This paper has been subjected to agency review and approved for publication.

REFERENCES

1. *Research Priorities for Airborne Particulate Matter: II. Evaluating Research Progress and Updating the Portfolio*; National Academy Press: Washington, DC, 1999.
2. U.S. Environmental Protection Agency. Office of Transportation and Air Quality Home Page. Available at: http://www.epa.gov/otaq/mobile.htm (accessed July 2003).
3. *Modeling Mobile-Source Emissions*; National Academy Press: Washington, DC, 2000.
4. California Air Resources Board. On-Road Motor Vehicle Emission Inventory Models Home Page. Available at: http://www.arb.ca.gov/msei/msei.htm (accessed July 2003).
5. Singh, R.B.; Huber, A.H. Sensitivity Analysis and Evaluation of MicroFacCO: A Microscale Motor Vehicle Emission Factor Model for CO Emissions; *J. Air & Waste Manage. Assoc.* **2001**, *51* (7), 1087-1099.
6. Singh, R.B.; Huber, A.H. Development of a Microscale Emission Factor Model for CO for Predicting Real-Time Motor Vehicle Emissions; *J. Air & Waste Manage. Assoc.* **2000**, *50* (11), 1980-1991.
7. *User's Guide to MOBILE6, Mobile Source Emission Factor Model*; EPA420-D-01–002a; U.S. Environmental Protection Agency: Ann Arbor, MI, 2001.
8. MOBILE6 Vehicle Emission Modeling Software Home Page. Available at: http://www.epa.gov/otaq/m6.htm (accessed July 2003).
9. *Evaluation of MOBILE Vehicle Emission Model*; DTRS-57–89-D-00089; Prepared for the U.S. Department of Transportation by Sierra Research, Inc.: Sacramento, CA, 1994.
10. U.S. Environmental Protection Agency. Proposed Rules, 40 CFR Part 86; *Fed. Regist.* **1997**, *62*, 44753.
11. Highway Vehicle Particulate Emission Modeling Software PART5 Home Page. Available at: http://www.epa.gov/otaq/part5.htm (accessed July 2003).
12. *Current Fuels and Emission Research*; College of Engineering, Center for Environmental Research and Technology (CE-CERT), University of California: Riverside, CA, 1999.
13. Rijkeboer, R.; Hendriksen, P. *Regulated and Unregulated Exhaust Gas Components from Light-Duty Vehicles on Petrol, Diesel, LPG and CNG;* TNO Report 93; Organization for Applied Scientific Research: Delft, The Netherlands, 1993.
14. Lies, K. *Unregulated Motor Vehicle Exhaust Gas Components*; Volkswagen AG Report; Research Physicochemical Metrology: Wolfsburg, Germany, 1989.
15. Siegel, W.O.; Zinbo, M.; Korniski, T.J.; Richert, J.F.O.; Chladek, E.; Paputa Peck, M.C.; Weir, J.E., Schuetzle, D.; Jensen, T.E. Air Toxics: A Comparison of the Gas-and Particle-Phase Emissions from a High-Emitter Vehicle with Those from a Normal-Emitter Vehicle. SAE Technical Paper 940581; Society of Automotive Engineers: Warrendale, PA, 1994.
16. Zinbo, M.; Korniski, T.J.; Weir, J.E. Relationship between the Composition of Engine Particulate Emissions and Emission Control System Performance; *Indust. Eng. Chem. Res.* **1995**, *34* (2), 619-625.
17. Westerholm, R.; Christensen, A.; Rosen, A. Regulated and Unregulated Exhaust Emissions from Two Three-Way Catalyst Equipped Gasoline Fuelled Vehicles; *Atmos. Environ.* **1996**, *30* (20), 3529-3536.
18. Norbeck, J.M.; Durbin, T.D.; Truex, T.J. *Measurement of Primary Particulate Matter Emissions from Light-Duty Motor Vehicles*; Final Report, CRC Project E-24-2; Coordinating Research Council: Alpharetta, GA, 1998.
19. Durbin, T.D.; Norbeck, J.M.; Smith, M.R.; Truex, T.J. Particulate Emission Rates from Light-Duty Vehicles in the South Coast Air Quality Management District; *J. Environ. Sci. Technol.* **1999**, *33* (24), 4401-4406.
20. Maricq, M.M.; Podsiadlik, D.H.; Chase, R.E. Examination of the Size-Resolved and Transient Nature of Motor Vehicle Particle Emissions *J. Environ. Sci. Technol.* **1999**, *33* (10), 1618-1626.
21. Maricq, M.M.; Podsiadlik, D.H.; Chase, R.E. Gasoline Vehicle Particle Size Distributions: Comparison of Steady State, FTP, and US06 Measurements; *J. Environ. Sci. Technol.* **1999**, *33* (12), 2007-2015.
22. Chase, R.E.; Duszkiewicz, G.J.; Jensen, T.E.; Lewis, D.; Schlaps, E.J.; Weibel, A.T.; Cadle, S.; Mulawa, P. Particle Mass Emission Rates from Current-Technology, Light-Duty Gasoline Vehicles; *J. Air & Waste Manage. Assoc.* **2000**, *50*, 930-935.
23. Sawyer, R.F.; Harley, R.A.; Cadle, S.H.; Norbeck, J.M.; Slott, R.; Bravo, H.A. Mobile Sources Critical Review: 1998 NARSTO Assessment; *Atmos. Environ.* **2000**, *34*, 2161-2181.
24. Gertler, A.W.; Gillies, J.A.; Pierson, W.R.; Rogers, C.F.; Sagebiel, J.C.; Abu-Allaban, M.; Coulombe, W.; Tarnay, L.; Cahill, T.A. *Ambient Sampling of Diesel Particulate Matter*; Draft Final Report; Desert Research Institute: Reno, NV, 2000.
25. Jackson, T.R. *Fleet Characterization Data for MOBILE6: Development and Distribution of Age Distributions, Average Annual Mileage Accumulation Rates, and Projected Vehicle Counts for Use in MOBILE6*; EPA420-P-99–011; U.S. Environmental Protection Agency, Office of Mobile Sources: Ann Arbor, MI, 1999.
26. Lang, J.M.; Snow, R.; Carlson, R.; Black, F.; Zweidinger, R.B.; Tejada, S. Characterization of Particulate Emissions from In-Use Gasoline-fueled Motor Vehicles. SAE Technical Paper 811186; Society of Automotive Engineers: Warrendale, PA, 1981.
27. Hildemann, L.M.; Markowski, G.R.; Cass, G.R. Chemical Composition of Emissions from Urban Sources of Fine Organic Aerosol; *J. Environ. Sci. Technol.* **1991**, *25*, 744.
28. Rogge, W.F.; Hildemann, L.M.; Mazurek, M.A. Sources of Fine Organic Aerosol. 2. Noncatalyst and Catalyst-Equipped Automobiles and Heavy-Duty Trucks; *J. Environ. Sci. Technol.* **1993**, *27*, 636-651.
29. Williams, D.J.; Miline, J.W.; Roberts, D.B. Particulate Emissions from "In-Use" Motor Vehicles—I. Spark Ignition Vehicles; *Atmos. Environ.* **1989**, *23* (12), 2639-2645.
30. Cadle, S.H.; Mulawa, P.; Groblicki, P.; Laroo, C.; Ragazzi, R.A.; Nelson, K.; Gallagher, G.; Zielinska, B. In-Use Light-Duty Gasoline Vehicle Particulate Matter Emissions on Three Driving Cycles; *J. Environ. Sci. Technol.* **2001**, *35*, 26-32.
31. Cadle, S.H.; Mulawa, P.; Groblicki, P.; Laroo, C.; Ragazzi, R.A.; Nelson, K.; Gallagher, G.; Zielinska, B. *In-Use Light-Duty Gasoline Vehicle Particulate Matter Emissions on Three Driving Cycles*; Final Report, CRC Project E-46; Coordinating Research Council: Alpharetta, GA, 1999.
32. Sagebiel, J.C.; Zielinska, B.; Walsh, P.A.; Chow, J.C.; Cadle, S.H.; Mulawa, P.A.; Knapp, K.T.; Zweidinger, R.B.; Snow, R.P.M. Ten Exhaust Samples Collected during IM-240 Dynamometer Tests of In-Service Vehicles in Nevada; *J. Environ. Sci. Technol.* **1997**, *31* (1), 75-83.
33. Cadle, S.H.; Mulawa, P.A.; Ball, J.; Donase, C.; Weibel, A.; Sagebiel, J.C.; Knapp, K.T.; Snow, R. Particulate Emission Rates from In-Use High-Emitting Vehicles Recruited in Orange County, California; *J. Environ. Sci. Technol.* **1997**, *31* (12), 3405-3412.
34. Eggleston, H.S.; Gaudioso, D.; Gorissen, N.; Joumard R.; Rijkeboer, R.C.; Samaras, Z.; Zierock, K.H. *CORINAIR Working Group on Emission Factors for Calculating 1990 Emissions from Road Traffic. Volume 1: Methodology and Emission Factors;* Contract Number B4–3045 (91) 10PH; Commission of the European Communities, DG XI-EEA Task Force: Brussels, 1991.
35. Williams, D.J.; Miline, J.W.; Quigley, S.M.; Roberts, D.B. Particulate Emissions from "In-Use" Motor Vehicles—II. Diesel Vehicles; *Atmos. Environ.* **1989**, *23* (12), 2647-2661.
36. *Airborne Particulate Matter in the United Kingdom*; Third Report of the Quality of Urban Air Review Group (QUARG); Department of Environment: Birmingham, UK, 1996.
37. Lindhjem, C.; Jackson, T. *Update of Heavy-Duty Emission Levels (Model Years 1988–2004+) for Use in MOBILE6*; EPA420-R-99–010; U.S.

Environmental Protection Agency Office of Mobile Sources, Ann Arbor, MI, 1999.
38. Bata, R.; Yacoub, Y.; Wang, W.; Lyons, D.W.; Gambino, M.; Rideout, G. SAE Technical Paper 942263; Society of Automotive Engineers: Warrendale, PA, 1994.
39. Yanowitz, J.; McCormick, R.L.; Graboski, M.S. In-Use Emissions from Heavy-Duty Diesel Vehicles; *J. Environ. Sci. Technol.* **2000**, *34* (5), 729-740.
40. Cha, S.; Carter, P.; Bradow, R.L. Simulation of Automobile Brake-Wear Dynamics and Estimate of Emissions. SAE Technical Paper 831036; Society of Automotive Engineers: Warrendale, PA, 1983.
41. Pierson, W.R.; Bracachzek, W.M. Airborne Particulate Debris from Rubber Tires; *Rubber Chem. Technol.* **1974**, *47* (5), 1215-1229.
42. Cadle, S.H.; Williams, R.L. Gas and Particle Emissions from Automobile Tires in Laboratory; *J. Air Pollut. Control Assoc.* **1978**, *28* (5), 502-507.
43. Fitzpatrick, M. *Emission Control Technologies and Emission Factors for Unpaved Road Fugitive Emissions, User's Guide*; EPA/625/5–87/022; U.S. Environmental Protection Agency: Cincinnati, OH, 1987.
44. Claiborn, C.; Mitra, A.; Adams, G.; Bamesberger, L.; Allwine, G.; Kantamaneni, R.; Lamb, B.; Westberg, H. Evaluation of PM_{10} Emission Rates from Paved and Unpaved Roads Using Tracer Techniques; *Atmos. Environ.* **1995**, *29* (10), 1075-1089.
45. Muleski, G.E.; Stevens, K. PM_{10} Emission from Public Unpaved Roads in Rural Arizona. In *Transactions, PM_{10} Standards and Nontraditional Particulate Control*; A&WMA: Pittsburgh, PA, 1992; pp 324-334.
46. Zimmer, R.A.; Reeser, W.K.; Cummins, P. Evaluation of PM_{10} Emission Factors for Paved Streets. . In *Transactions, PM_{10} Standards and Nontraditional Particulate Control*; A&WMA: Pittsburgh, PA, 1992; pp 311-323.
47. Kantamaneni, R.; Adams, G.; Bamesberger, L.; Allwine, G.; Westberg, H.; Lamb, B.; Claiborn, C. The Measurement of Roadway PM_{10} Emission Rates Using Tracer Ratio Techniques; *Atmos. Environ.* **1996**, *30* (24), 4209-4233.
48. Kinsey, J.S. *Characterization of PM_{10} Emissions from Antiskid Material Applied to Ice and Snow Covered Roadways*; EPA/600/R-93/019; U.S. Environmental Protection Agency: Research Triangle Park, NC, 1993.
49. Singh, R.B.; Colls, J.J. Development and Preliminary Evaluation of a Particulate Matter Emission Factor Model (PMFAC) for European Motor Vehicles; *J. Air & Waste Manage. Assoc.* **2000**, *50* (10), 1805-1817.
50. *AP-42: Compilation of Air Pollutant Emission Factors—Mobile Sources*; U.S. Environmental Protection Agency: Ann Arbor, MI, 1998.
51. Lawson, D.R.; Walsh, P.A.; Switzer, P. *Effectiveness of U.S. Motor Vehicle Inspection/ Maintenance Programs, 1985–1992;* Final report prepared for California I/M Review Committee; Prepared by Desert Research Institute: Reno, NV, 1995.
52. Singh, R.B.; Colls, J.J. Development of Particulate Emission Factors and Size Distributions for European Motor Vehicles. Presented at the 90th Annual Conference & Exhibition of A&WMA, Toronto, Ontario, Canada, June 1997; Paper 97-WP96.01.
53. Singh, R.B.; Colls, J.J. Development of a Particulate Emission Factor Model for European Motor Vehicles. Presented at the 90th Annual Conference & Exhibition of A&WMA, Toronto, Ontario, Canada, June 1997; Paper 97-RP143.01.
54. Hickman, A.J. Transport Research Laboratory, Berkshire, United Kingdom. Personal communication, 1995.
55. Koupal, J. *Air Conditioning Correction Factors in MOBILE6*; U.S. Environmental Protection Agency: Ann Arbor, MI, 1998.
56. Koupal, J. *Air Conditioning Activity Effects in MOBILE6;* U.S. Environmental Protection Agency: Ann Arbor, MI, 1998.
57. Meisner, B.N.; Graves, L.F. Apparent Temperature; *Weatherwise* **1985**, *August*, 211-213.
58. Norbeck, J.M.; Durbin, T.D.; Truex, T.J.; Smith, M.R. *Characterizing Particulate Emissions from Medium and Light Heavy-Duty Diesel-Fueled Vehicles*; Final Report; CE-CRT Contract 97031; Submitted to South Coast Air Quality Management District, Technology Advancement Office; Center for Environmental Research and Technology: Riverside, CA, 1998.
59. Kleeman, M.J.; Schauer, J.J.; Cass, G.R. Size and Composition Distribution of Fine Particulate Matter Emitted from Motor Vehicles; *J. Environ. Sci. Technol.* **2000**, *34* (7), 1132-1142.
60. Singh, R.B.; Huber, A.H.; Braddock, J.N. Sensitivity Analysis and Evaluation of MicroFacPM: A Microscale Motor Vehicle Emission Factor Model for PM Emissions; *J. Air & Waste Manage. Assoc.*, submitted for publication.
61. Jackson, T.R. *Fleet Characterization Data for MOBILE6: Development and Distribution of Age Distributions, Average Annual Mileage Accumulation Rates, and Projected Vehicle Counts for Use in MOBILE6*; EPA420-P-99–011; U.S. Environmental Protection Agency, Office of Mobile Sources: Ann Arbor, MI, 1999.
62. Browning, L.; Chan, M.; Coleman, D.; Pera, C. *Update of Fleet Characterization Data for Use in MOBILE6-Final Report*; EPA420-P-98–016; U.S. Environmental Protection Agency, Office of Mobile Sources: Ann Arbor, MI, 1998.
63. Singh, R.B.; Huber, A.H.; Braddock, J.N. Modeling and Measurement of Real-Time CO Concentrations in Roadway Microenvironments. Presented at the 93rd Annual Conference & Exhibition of A&WMA, Salt Lake City, UT, June 2000; Paper 00-339.

About the Authors
Rakesh B. Singh was a National Research Council research associate at the National Exposure Research Laboratory in Research Triangle Park, NC; currently, he is an independent contractor with MicroEnvironmental Consulting Services, Kitchener, Ontario, Canada. Dr. Singh has been working on microscale emission modeling since 1994. Alan H. Huber, QEP, is on assignment to the National Exposure Research Laboratory from the Atmospheric Sciences Modeling Division of the Air Resources Laboratory, part of the National Oceanic and Atmospheric Administration, in Research Triangle Park, NC. Dr. Huber has been working on microscale air pollution modeling since 1974. James N. Braddock is also with the National Exposure Research Laboratory. Dr. Braddock has measured and characterized mobile source pollutants since 1974. Address correspondence to: Dr. Alan H. Huber, National Exposure Research Laboratory, U.S. Environmental Protection Agency, Mail-Code E243, Research Triangle Park, NC 27711; e-mail: huber.alan@epa.gov.